JC16 Rec'd PCT/PTO SEP 17 2001

FORM PTO-1390 (REV 10-2000) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE **TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371**		ATTORNEY'S DOCKET NUMBER CU-2649 RJS U.S. APPLICATION NO. (If known, see 37 CFR 1.5) 09/936775
INTERNATIONAL APPLICATION NO. PCT/AU00/00219	INTERNATIONAL FILING DATE 20 March 2000	PRIORITY DATE CLAIMED 18 March 1999

TITLE OF INVENTION
WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

APPLICANT(S) FOR DO/EO/US
Michael BAZYLENKO et al

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. [X] This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. [ ] This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. [X] This is an express request to promptly begin national examination procedures (35 U.S.C. 371(f)).
4. [X] The US has been elected by the expiration of 19 months from the priority date (PCT Article 31).
5. [X] A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. [X] is attached hereto (required only if not communicated by the International Bureau).
   b. [ ] has been communicated by the International Bureau.
   c. [ ] is not required, as the application was filed in the United States Receiving Office (RO/US).
6. [ ] An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)).
7. [X] Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. [ ] are attached hereto (required only if not communicated by the International Bureau).
   b. [ ] have been communicated by the International Bureau.
   c. [ ] have not been made; however, the time limit for making such amendments has NOT expired.
   d. [X] have not been made and will not be made.
8. [ ] An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. [ ] An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. [ ] An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11 to 16 below concern document(s) or information included:

11. [ ] An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. [ ] An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. [X] A FIRST preliminary amendment.
    [ ] A SECOND or SUBSEQUENT preliminary amendment.
14. [X] A substitute specification.
15. [ ] A change of power of attorney and/or address letter.
16. [ ] Other items or information:

Express Mail Label No.:

L 698 182451

U.S. APPLICATION NO. (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO.	ATTORNEY'S DOCKET NUMBER
09/936775	PCT/AU00/00219	CU-2649 RJS

17. [X] The following fees are submitted:

	CALCULATIONS	PTO USE ONLY
BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)):		
Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1000.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO **$860.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$710.00**		
International preliminary examination fee paid to USPTO (37 CFR 1.482) but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$690.00**		
International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 1000.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than [ ] 20 [ ] 30 months from the earliest claimed priority date (37 CFR 1.492(e)).	$	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	25 -20 =	5	X **$18.00**	$ 90.00	
Independent claims	3 -3 =	0	X **$80.00**	$	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$270.00**	$	
TOTAL OF ABOVE CALCULATIONS =				$ 1090.00	
[ ] Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2.				$	
SUBTOTAL =				$ 1090.00	
Processing fee of **$130.00** for furnishing the English translation later than [ ] 20 [ ] 30 months from the earliest claimed priority date (37 CFR 1.492(f)). +				$	
TOTAL NATIONAL FEE =				$	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +				$	
TOTAL FEES ENCLOSED =				$ 1090.00	
				Amount to be refunded:	$
				charged:	$

a. [X] A check in the amount of $ 1090.00 to cover the above fees is enclosed.

b. [ ] Please charge my Deposit Account No. ____________ in the amount of $____________ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. [X] The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 12-0400. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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September 17, 2001

SIGNATURE:

Richard J. Streit
NAME

25765
REGISTRATION NUMBER

DOCKET: CU-2649

IN THE UNITED STATES PATENT & TRADEMARK OFFICE

APPLICANT: Michael BAZYLENKO et al)
)
TITLE: WAVEGUIDE STRUCTURE AND METHOD OF FORMING)
THE WAVEGUIDE STRUCTURE)
)
COMPLETION OF PCT/AU00/00219 filed 20 March 2000)

The Commissioner for Patents (DO/EO/US)
Box PCT
Washington, D.C. 20231

PRELIMINARY AMENDMENT

Dear Sir:

Please amend the application being filed herewith under 35 USC 371.

IN THE CLAIMS:

Please cancel claims 1-25 from the PCT application as filed as well as claims 1-21 from the claims filed in response to the Written Opinion on 04 July 2001 and substitute the clean version of claims 1-25 as attached to the substitute specification. Enclosed is a marked copy of the claims, showing changes made therein.

REMARKS

The claims have been amended to place the same in better condition for examination under U.S. rules of practice.

A substitute specification is enclosed and is based on the following materials:

- Pages 1-9 as attached to the International Preliminary Examination Report
- Pages 10-12 of the amended claims as referenced above
- Page 13 of the abstract as filed in the PCT international application
- 2 sheets of drawings as filed in the PCT international application

Favorable consideration of this application is respectfully requested.

Respectfully submitted,

September 17, 2001
Date

Attorney for Applicant

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SUBSTITUTE SPECIFICATION

Proposed Amended Claims

We claim:

~~The claims defining the invention are~~

1. A method for forming a high optical confinement waveguide structure, the method comprising the step of:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate;

wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

2. A method as claimed in claim 1, further comprising the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in claim~~s~~ 2 ~~or 3~~, wherein the first layer is silica-based.

5. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner such as to form a ridge structure in the deposited waveguide layer.

7. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the method further comprises the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure.

8. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the method further comprises the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide.

9. A method as claimed in claim 8, wherein the step of varying the refractive index comprises exposing the

deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

10. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the silicon containing material comprises a dopant material.

11. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

12. A method as claimed in claim 11, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

13. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the method further comprises crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer.

14. A method as claimed in claim 13, wherein the step of crystallising comprises utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the silicon containing material to control a grain size in the crystallised waveguide.

15. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the step of forming the waveguide comprises plasma enhanced chemical vapour deposition (PECVD).

16. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the step of forming the waveguide comprises forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre.

17. A method as claimed in claim 16, wherein the step of forming the taper comprises varying the refractive

index of the deposited waveguide layer in the end portion of the waveguide.

18. A method as claimed in claim 17, wherein the varying of the refractive index in the end portion comprises controlled oxidation of the deposited waveguide layer.

19. A method as claimed in claim 18, wherein the controlled oxidation comprises a laser to heat the deposited waveguide layer.

20. A method as claimed in claim 19, wherein the laser comprises a CO_2 laser.

21. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

22. A method as claimed in claim 22, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

23. A method as claimed in claim 22, wherein the processing element is arranged to be controlled electrically to change its refractive index.

24. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of:

- oxidizing the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling;

wherein the oxidizing is controlled in a manner such that a refractive index profile is created in the end portion, and wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

25. An optical device incorporating a silicon-based waveguide structure on a substrate formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure.

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WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

Field of the Invention

The present invention relates broadly to a high-optical-confinement waveguide structure and a method for forming the same.

Background of the Invention

High-confinement optical waveguides rely on a high refractive index contrast between the waveguide material and surrounding cladding material/optically isolating layers. This allows the design of very compact waveguide structures, which have found numerous applications enabling dramatic reduction in device dimensions while maintaining the required optical functionality.

Recently, silicon has been identified as a suitable material for the production of high confinement waveguide structures. Silicon has a high refractive index of the order of 4 at 1.5 a wavelength of about 1.5 µm. High confinement optical waveguides based on silicon as the waveguide core material are presently manufactured utilising a technique known as "Separation by Implanted Oxygen" (SIMOX) to create Silicon on Insulator (SOI) structures. In the SIMOX technique, oxygen is implanted into a silicon wafer. The wafer is then annealed to form a silicon layer above a layer of oxidised silicon formed from the implanted oxygen at a predetermined implantation depth.

However, this technique suffers from several disadvantages including the high cost related to the

complex fabrication of SIMOX substrates, and the limited range of variations in the parameters of the SIMOX substrates, such as the limited range of the waveguide material properties (bulk silicon) and the limited range of achievable thicknesses of the oxidised optical isolation layer created through oxygen implantation.

Summary of the Invention

The present invention provides a method for forming a high-optical-confinement waveguide structure, the method comprising:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer comprising amorphous silicon onto the substrate;

wherein the waveguide layer has a refractive index which is greater than a refractive index of the substrate.

Accordingly, thin film technology can be used to fabricate high optical confinement silicon-based waveguide structures, which can increase the range of properties of the silicon-based waveguide of the waveguide structure.

The method may further comprise a step of depositing a first layer of a first material on a wafer so as to form the substrate prior to depositing the waveguide layer. The wafer may comprise a silicon wafer. The first layer may be silica-based.

The step of forming the silicon-based waveguide may further comprise etching the deposited waveguide layer. The etching may be performed in a manner which forms a ridge structure in the deposited waveguide layer. The method may further comprise a step of depositing a second layer of a second material so as to form an etch-stop, whereby to enable the formation of the ridge structure. Accordingly, the height of the ridge structure can be more

accurately controlled compared to relying on uniformity of the etching process.

The method may further comprise a step of creating a refractive index variation in the deposited waveguide layer so as to form a non-constant refractive index profile in the waveguide layer. The step of creating the refractive index variation may comprise exposing the deposited waveguide layer to radiation so as to induce refractive index changes in the deposited waveguide layer.

The waveguide layer may further comprise a dopant material.

The deposited waveguide layer may further comprise at least partially-oxidised silicon.

The method may further comprise crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer. The step of crystallising may comprise utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the first material to control a grain size in the crystallised waveguide.

The waveguide may be deposited by plasma enhanced chemical vapour deposition (PECVD).

The step of forming the waveguide may further comprise forming a taper in an end portion of the deposited waveguide layer for facilitating optical coupling to an optical fibre. The step of forming the waveguide further comprises creating a variation of refractive index of the deposited waveguide layer in the end portion of the waveguide. The step of creating the variation of the refractive index in the end portion may comprise carrying out controlled oxidation of the end portion. The controlled oxidation may comprise using a

laser to heat the deposited waveguide layer. The laser may comprise a CO_2 laser.

The method may further comprise a step of forming a processing element in and integrated with the deposited waveguide layer.

The present invention may alternatively be defined as an optical device incorporating a silicon-based waveguide structure formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure, wherein the silicon-based waveguide structure incorporates an amorphous-silicon-based waveguide layer.

The processing element may comprise a photodetector incorporating a dopant material in the silicon-based waveguide structure.

The present invention may alternatively be defined as providing a method of coupling a silicon-based waveguide to an optical fibre, the method comprising: - oxidising the silicon-based waveguide in an end portion thereof so as to alter a refractive index of the end portion; wherein the end portion is arranged to facilitate optical coupling of the waveguide to an end of an optical fibre, the oxidation being controlled so as to create a refractive index profile in which the refractive index at an outer end of the end portion matches that of the optical fibre.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1a to e are schematic drawings illustrating a method of forming a waveguide structure embodying the present invention.

Figure 2 is a schematic drawing illustrating a method of coupling a waveguide structure to an optical fibre embodying the present invention.

Detailed Description of the Preferred Embodiment

In Figure 1a, a silicon wafer 10 is the starting substrate for subsequent thin film deposition of the various layers of the high optical confinement waveguide structure as described below.

Turning to Figure 1b, as a first step a silica buffer layer 12 is deposited on the silicon wafer 10 using Plasma Enhanced Chemical Vapour Deposition (PECVD) using a suitably oxidised silane precursor. The silica buffer layer 12 typically comprises a silicon dioxide, resulting in a refractive index of 1.46 (at 1.5 micro meter wavelength) of the buffer layer 12.

Next, as shown in Figure 1c, a waveguide layer 14 of amorphous silicon is deposited using again PECVD from a silane precursor.

It is noted that the refractive index of the resultant waveguide layer 14 can be adjusted from that of pure amorphous silicon (3.6 to 3.8 at a wavelength of 1.5 μm) to that of silicon dioxide (1.46 at wavelength of 1.5 μm) by controlled oxidation of the silane during the PECVD process. This allows a great range of material properties of the waveguide layer 14, which in turn gives design flexibility for devices incorporating the high confinement optical waveguide.

In the next processing step, photolithography and reactive ion etching are used to produce a ridge 16 in the amorphous silicon layer which defines the high confinement

optical waveguide. The height of the ridge 16 determines the degree of optical confinement, wherein the higher the ridge 16 is, the higher the optical confinement (see Figure 1d).

Finally, as illustrated in Figure 1e, a further silica layer 18 is deposited to form an outer cladding of the waveguide structure.

It will be appreciated by a person skilled in the art that the above described method allows control over various properties of the resultant high optical confinement waveguide structure.

Those include the control over the refractive index of the silicon-waveguide layer 14 as mentioned before, and the semiconductor properties of the silicon layer 14 (e.g. carrier lifetime which may be adjusted through suitable dopants). Furthermore, the thickness/height of the ridge 16 can be conveniently controlled, as well as the thickness and composition of the buffer layers 12 and 18.

The refractive index of the silicon layer 14 may further be altered through solid phase crystallisation of the deposited amorphous silicon layer 14 by high temperature processing, such as rapid thermal annealing (RTA) or laser heating. It is noted here that the formation of grains caused by the crystallisation can cause an access scattering loss of the resultant waveguide. However, the grain size can be controlled independently by an appropriate doping of the silicon layer so that the high temperatures required to achieve the necessary re-crystallisation to eg. control the semiconductor properties of the silicon layer 12 do not lead to an excessive grain growth. In one embodiment,

small amounts of oxygen can be incorporated during the deposition of the silicon layer 14, which can significantly restrain the grain growth even at temperatures in excess of 800ºC.

The above described method can for example be utilised to construct silicon-based thermo-optical switches (TOS) and switching matrices. Despite the high thermo-optic coefficient of silicon it has so far been difficult to realise TOS, as in the SIMOX process little thermal isolation of the silicon waveguide from the highly thermally conductive silicon substrate could be achieved. This is a result of the small thickness of the barrier oxide layer formed from the implanted oxygen dictated by the SIMOX process.

In the embodiment of the present invention described above, the thickness of the silica buffer layer 12 can be varied conveniently in a sufficient thickness range as it utilises thin film technology rather than relying on implantation of oxygen into a substrate. Therefore, heat losses into the silicon substrate in TOS and switching matrices can be minimised, which in turn reduces the thermo-optical switching power required.

It will be appreciated by a person skilled in the art that the above described method can be utilised in the construction of other device structures, including for example devices which incorporate a processing element which is arranged to be controlled electrically to change its refractive index. Such processing elements can be useful in for example electro-optic modulator devices or phase shifter devices.

An advantage of another embodiment of the present invention will be described.

In silicon-based opto-electronics it is often required to couple light to and from an optical fibre. Typically, the coupling losses are high due to an optical mode mismatch between silica (fibre) and silicon systems. One solution to this problem is to provide adiabatic tapering to the input/output silicon waveguides in order to expand their optical mode towards the optical mode of the fibres. However, this requires relatively large tapering distances to avoid radiation losses which partially negates the advantages of the compactness of the optical circuits as such.

Turning now to Figure 2, in an embodiment of the present invention a silicon waveguide 30 comprises a tapered end portion 32 for mode matching to an optical fibre 34 resting in a groove (not shown) of a carrier substrate 36. In this embodiment, controlled oxidation of the deposited amorphous silicon waveguide 30 is utilised to reduce the length of the required tapering 32. A laser beam 38 is scanned locally in the tapered end portion 32 of the amorphous silicon waveguide 30 to oxidise the amorphous silicon in that region, thereby reducing its refractive index in that region towards that of silica. This allows for a reduction in the length of the required tapering 32. In this embodiment, a CO_2 laser is used, but it will be appreciated that other lasers could be used to locally oxidise the amorphous silicon.

A refractive index profile in the tapered region 32 can be achieved by controlling the degree of oxidation, which will depend on the laser pulse frequency and exposure duration.

In another embodiment of the present invention, deposition of germanium-doped silicon waveguide layers can introduce infrared absorption which in turn will allow incorporating a signal receive function in the waveguide. Accordingly, embodiments of the present invention can provide integrated active and passive circuit components.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprising" is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.

We Claim:

1. A method for forming a high optical confinement waveguide structure, the method comprising the step of:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate;

wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

2. A method as claimed in claim 1, further comprising the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in claim 2, wherein the first layer is silica-based.

5. A method as claimed in claim 1, wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner such as to form a ridge structure in the deposited waveguide layer.

7. A method as claimed in claim 1, wherein the method further comprises the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure.

8. A method as claimed in claim 1, wherein the method further comprises the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide.

9. A method as claimed in claim 8, wherein the step of varying the refractive index comprises exposing the deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

10. A method as claimed in claim 1, wherein the silicon containing material comprises a dopant material.

11. A method as claimed in claim 1, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

12. A method as claimed in claim 11, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidized silicon.

13. A method as claimed in claim 1, wherein the method further comprises crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer.

14. A method as claimed in claim 13, wherein the step of cystallising comprises utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the silicon containing material to control a grain size in the crystallised waveguide.

15. A method as claimed in claim 1, wherein the step of forming the waveguide comprises plasma enhanced chemical vapour deposition (PECVD).

16. A method as claimed in claim 1, wherein the step of forming the waveguide comprises forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre.

17. A method as claimed in claim 16, wherein the step of forming the taper comprises varying the refractive index of the deposited waveguide layer in the end portion of the waveguide.

18. A method as claimed in claim 17, wherein the varying of the refractive index in the end portion comprises controlled oxidation of the deposited waveguide layer.

19. A method as claimed in claim 18, wherein the controlled oxidation comprises a laser to heat the deposited waveguide layer.

20. A method as claimed in claim 19, wherein the laser comprises a CO_2 laser.

21. A method as claimed in claim 1, wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

22. A method as claimed in claim 22, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

23. A method as claimed in claim 22, wherein the processing element is arranged to be controlled electrically to change its refractive index.

24. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of:

- oxidizing the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling;

wherein the oxidizing is controlled in a manner such that a refractive index profile is created in the end portion, and wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

25. An optical device incorporating a silicon-based waveguide structure on a substrate formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure.

ABSTRACT

A method for forming a high optical confinement waveguide structure comprising the steps of: forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate; wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate; wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide structure such as to form a ridge structure in the deposited waveguide layer; wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

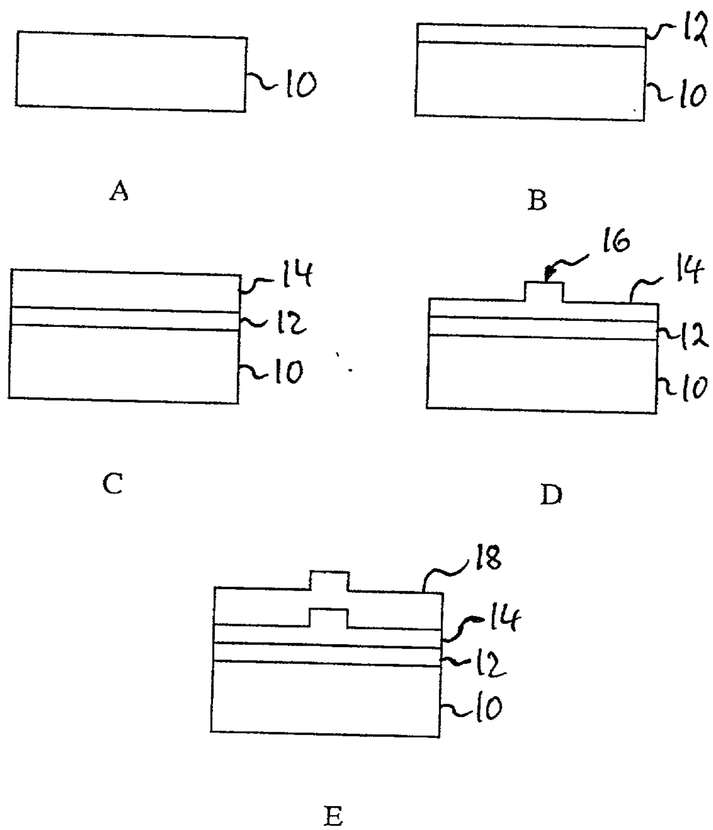

Figure 1

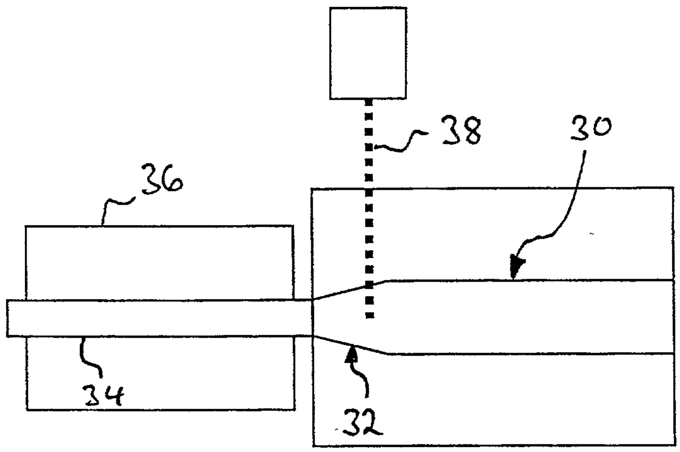

Figure 2

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WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

Field of the Invention

The present invention relates broadly to a high-optical-confinement waveguide structure and a method for forming the same.

Background of the Invention

High-confinement optical waveguides rely on a high refractive index contrast between the waveguide material and surrounding cladding material/optically isolating layers. This allows the design of very compact waveguide structures, which have found numerous applications enabling dramatic reduction in device dimensions while maintaining the required optical functionality.

Recently, silicon has been identified as a suitable material for the production of high confinement waveguide structures. Silicon has a high refractive index of the order of 4 at 1.5 a wavelength of about 1.5 μm. High confinement optical waveguides based on silicon as the waveguide core material are presently manufactured utilising a technique known as "Separation by Implanted Oxygen" (SIMOX) to create Silicon on Insulator (SOI) structures. In the SIMOX technique, oxygen is implanted into a silicon wafer. The wafer is then annealed to form a silicon layer above a layer of oxidised silicon formed from the implanted oxygen at a predetermined implantation depth.

However, this technique suffers from several disadvantages including the high cost related to the

complex fabrication of SIMOX substrates, and the limited range of variations in the parameters of the SIMOX substrates, such as the limited range of the waveguide material properties (bulk silicon) and the limited range of achievable thicknesses of the oxidised optical isolation layer created through oxygen implantation.

Summary of the Invention

The present invention provides a method for forming a high-optical-confinement waveguide structure, the method comprising:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer comprising amorphous silicon onto the substrate;

wherein the waveguide layer has a refractive index which is greater than a refractive index of the substrate.

Accordingly, thin film technology can be used to fabricate high optical confinement silicon-based waveguide structures, which can increase the range of properties of the silicon-based waveguide of the waveguide structure.

The method may further comprise a step of depositing a first layer of a first material on a wafer so as to form the substrate prior to depositing the waveguide layer. The wafer may comprise a silicon wafer. The first layer may be silica-based.

The step of forming the silicon-based waveguide may further comprise etching the deposited waveguide layer. The etching may be performed in a manner which forms a ridge structure in the deposited waveguide layer. The method may further comprise a step of depositing a second layer of a second material so as to form an etch-stop, whereby to enable the formation of the ridge structure. Accordingly, the height of the ridge structure can be more

accurately controlled compared to relying on uniformity of the etching process.

The method may further comprise a step of creating a refractive index variation in the deposited waveguide layer so as to form a non-constant refractive index profile in the waveguide layer. The step of creating the refractive index variation may comprise exposing the deposited waveguide layer to radiation so as to induce refractive index changes in the deposited waveguide layer.

The waveguide layer may further comprise a dopant material.

The deposited waveguide layer may further comprise at least partially-oxidised silicon.

The method may further comprise crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer. The step of crystallising may comprise utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the first material to control a grain size in the crystallised waveguide.

The waveguide may be deposited by plasma enhanced chemical vapour deposition (PECVD).

The step of forming the waveguide may further comprise forming a taper in an end portion of the deposited waveguide layer for facilitating optical coupling to an optical fibre. The step of forming the waveguide further comprises creating a variation of refractive index of the deposited waveguide layer in the end portion of the waveguide. The step of creating the variation of the refractive index in the end portion may comprise carrying out controlled oxidation of the end portion. The controlled oxidation may comprise using a

laser to heat the deposited waveguide layer. The laser may comprise a CO_2 laser.

The method may further comprise a step of forming a processing element in and integrated with the deposited waveguide layer.

The present invention may alternatively be defined as an optical device incorporating a silicon-based waveguide structure formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure, wherein the silicon-based waveguide structure incorporates an amorphous-silicon-based waveguide layer.

The processing element may comprise a photodetector incorporating a dopant material in the silicon-based waveguide structure.

The present invention may alternatively be defined as providing a method of coupling a silicon-based waveguide to an optical fibre, the method comprising: - oxidising the silicon-based waveguide in an end portion thereof so as to alter a refractive index of the end portion; wherein the end portion is arranged to facilitate optical coupling of the waveguide to an end of an optical fibre, the oxidation being controlled so as to create a refractive index profile in which the refractive index at an outer end of the end portion matches that of the optical fibre.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1a to e are schematic drawings illustrating a method of forming a waveguide structure embodying the present invention.

Figure 2 is a schematic drawing illustrating a method of coupling a waveguide structure to an optical fibre embodying the present invention.

Detailed Description of the Preferred Embodiment

In Figure 1a, a silicon wafer 10 is the starting substrate for subsequent thin film deposition of the various layers of the high optical confinement waveguide structure as described below.

Turning to Figure 1b, as a first step a silica buffer layer 12 is deposited on the silicon wafer 10 using Plasma Enhanced Chemical Vapour Deposition (PECVD) using a suitably oxidised silane precursor. The silica buffer layer 12 typically comprises a silicon dioxide, resulting in a refractive index of 1.46 (at 1.5 micro meter wavelength) of the buffer layer 12.

Next, as shown in Figure 1c, a waveguide layer 14 of amorphous silicon is deposited using again PECVD from a silane precursor.

It is noted that the refractive index of the resultant waveguide layer 14 can be adjusted from that of pure amorphous silicon (3.6 to 3.8 at a wavelength of 1.5 μm) to that of silicon dioxide (1.46 at wavelength of 1.5 μm) by controlled oxidation of the silane during the PECVD process. This allows a great range of material properties of the waveguide layer 14, which in turn gives design flexibility for devices incorporating the high confinement optical waveguide.

In the next processing step, photolithography and reactive ion etching are used to produce a ridge 16 in the amorphous silicon layer which defines the high confinement

optical waveguide. The height of the ridge 16 determines the degree of optical confinement, wherein the higher the ridge 16 is, the higher the optical confinement (see Figure 1d).

Finally, as illustrated in Figure 1e, a further silica layer 18 is deposited to form an outer cladding of the waveguide structure.

It will be appreciated by a person skilled in the art that the above described method allows control over various properties of the resultant high optical confinement waveguide structure.

Those include the control over the refractive index of the silicon-waveguide layer 14 as mentioned before, and the semiconductor properties of the silicon layer 14 (e.g. carrier lifetime which may be adjusted through suitable dopants). Furthermore, the thickness/height of the ridge 16 can be conveniently controlled, as well as the thickness and composition of the buffer layers 12 and 18.

The refractive index of the silicon layer 14 may further be altered through solid phase crystallisation of the deposited amorphous silicon layer 14 by high temperature processing, such as rapid thermal annealing (RTA) or laser heating. It is noted here that the formation of grains caused by the crystallisation can cause an access scattering loss of the resultant waveguide. However, the grain size can be controlled independently by an appropriate doping of the silicon layer so that the high temperatures required to achieve the necessary re-crystallisation to eg. control the semiconductor properties of the silicon layer 12 do not lead to an excessive grain growth. In one embodiment,

small amounts of oxygen can be incorporated during the deposition of the silicon layer 14, which can significantly restrain the grain growth even at temperatures in excess of 800ºC.

The above described method can for example be utilised to construct silicon-based thermo-optical switches (TOS) and switching matrices. Despite the high thermo-optic coefficient of silicon it has so far been difficult to realise TOS, as in the SIMOX process little thermal isolation of the silicon waveguide from the highly thermally conductive silicon substrate could be achieved. This is a result of the small thickness of the barrier oxide layer formed from the implanted oxygen dictated by the SIMOX process.

In the embodiment of the present invention described above, the thickness of the silica buffer layer 12 can be varied conveniently in a sufficient thickness range as it utilises thin film technology rather than relying on implantation of oxygen into a substrate. Therefore, heat losses into the silicon substrate in TOS and switching matrices can be minimised, which in turn reduces the thermo-optical switching power required.

It will be appreciated by a person skilled in the art that the above described method can be utilised in the construction of other device structures, including for example devices which incorporate a processing element which is arranged to be controlled electrically to change its refractive index. Such processing elements can be useful in for example electro-optic modulator devices or phase shifter devices.

An advantage of another embodiment of the present invention will be described.

In silicon-based opto-electronics it is often required to couple light to and from an optical fibre. Typically, the coupling losses are high due to an optical mode mismatch between silica (fibre) and silicon systems. One solution to this problem is to provide adiabatic tapering to the input/output silicon waveguides in order to expand their optical mode towards the optical mode of the fibres. However, this requires relatively large tapering distances to avoid radiation losses which partially negates the advantages of the compactness of the optical circuits as such.

Turning now to Figure 2, in an embodiment of the present invention a silicon waveguide 30 comprises a tapered end portion 32 for mode matching to an optical fibre 34 resting in a groove (not shown) of a carrier substrate 36. In this embodiment, controlled oxidation of the deposited amorphous silicon waveguide 30 is utilised to reduce the length of the required tapering 32. A laser beam 38 is scanned locally in the tapered end portion 32 of the amorphous silicon waveguide 30 to oxidise the amorphous silicon in that region, thereby reducing its refractive index in that region towards that of silica. This allows for a reduction in the length of the required tapering 32. In this embodiment, a CO_2 laser is used, but it will be appreciated that other lasers could be used to locally oxidise the amorphous silicon.

A refractive index profile in the tapered region 32 can be achieved by controlling the degree of oxidation, which will depend on the laser pulse frequency and exposure duration.

In another embodiment of the present invention, deposition of germanium-doped silicon waveguide layers can introduce infrared absorption which in turn will allow incorporating a signal receive function in the waveguide. Accordingly, embodiments of the present invention can provide integrated active and passive circuit components.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprising" is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.

THE CLAIMS

1. A method for forming a high-optical-confinement waveguide structure, the method comprising:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer comprising amorphous silicon onto the substrate;

wherein the waveguide layer has a refractive index which is greater than a refractive index of the substrate.

2. A method as claimed in claim 1, further comprising a step of depositing a first layer of a first material on a wafer so as to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in either claim 2 or 3, wherein the first layer is silica-based.

5. A method as claimed in any one of the preceding claims, wherein the step of forming the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner which forms a ridge structure in the deposited waveguide layer.

7. A method as claimed in any one of the preceding claims, wherein the method further comprises a step of

creating a refractive index variation in the deposited waveguide layer so as to form a non-constant refractive index profile in the waveguide layer.

8. A method as claimed in claim 7, wherein the step of creating the refractive index variation comprises exposing the deposited waveguide layer to radiation so as to induce refractive index changes in the deposited waveguide layer.

9. A method as claimed in any one of the preceding claims, wherein the waveguide layer further comprises a dopant material.

10. A method as claimed in any one of the preceding claims, wherein the deposited waveguide layer further comprises at least partially-oxidised silicon.

11. A method as claimed in any one of the preceding claims, wherein waveguide layer is deposited by plasma-enhanced chemical vapour deposition (PECVD).

12. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide further comprises forming a taper in an end portion of the deposited waveguide layer for facilitating optical coupling to an optical fibre.

13. A method as claimed in claim 12, wherein the step of forming waveguide further comprises creating a variation of refractive index of the deposited waveguide layer in the end portion of the waveguide.

14. A method as claimed in claim 13, wherein the step of creating the variation of refractive index in the end portion comprises carrying out controlled oxidation of the end portion.

15. A method as claimed in claim 14, wherein the controlled oxidation comprises using a laser to heat the deposited waveguide layer.

16. A method as claimed in claim 15, wherein the laser comprises a CO_2 laser.

17. A method as claimed in any one of the preceding claims, wherein the method further comprises a step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

18. A method as claimed in claim 17, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

19. A method as claimed in claim 18, wherein the processing element is arranged to be controlled electrically to change its refractive index.

20. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising:

- oxidising the silicon-based waveguide in an end portion thereof so as to alter a refractive index of the end portion; wherein the end portion is arranged to facilitate optical coupling of the waveguide to an end of

an optical fibre, the oxidation being controlled so as to create a refractive index profile in which the refractive index at an outer end of the end portion matches that of the optical fibre.

21. An optical device incorporating a silicon-based waveguide structure formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure, wherein the silicon-based waveguide structure incorporates an amorphous-silicon-based waveguide layer.

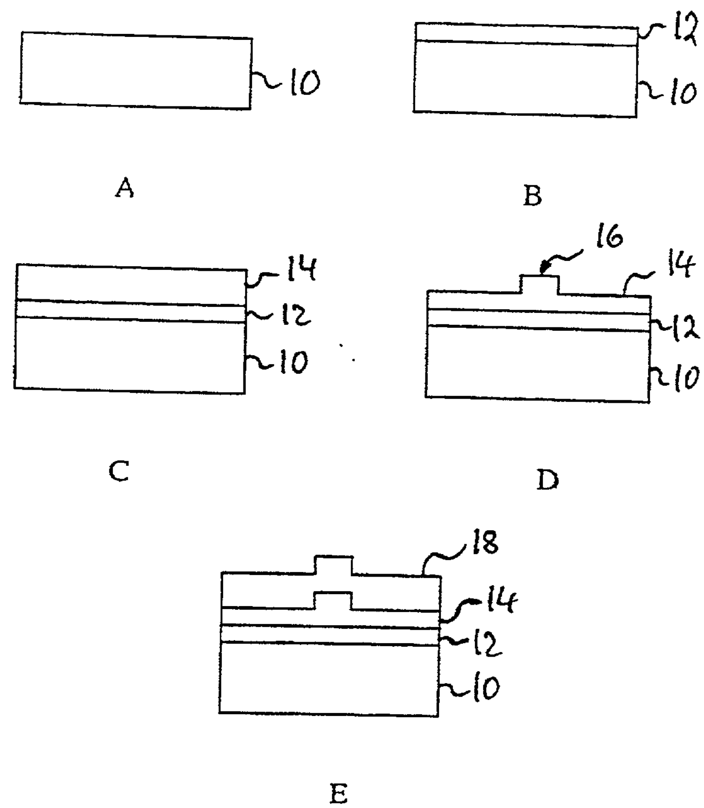

Figure 1

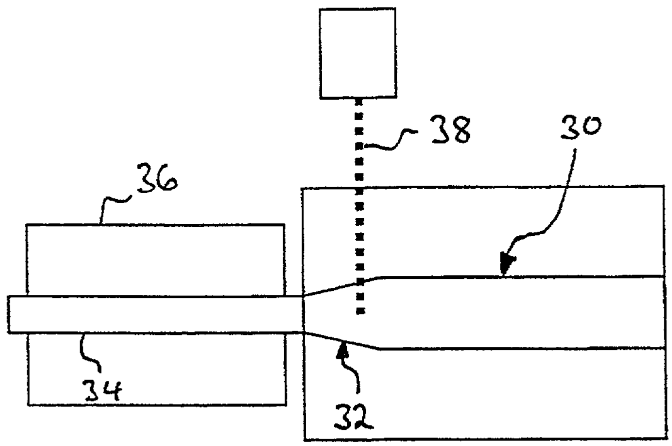

Figure 2

CPC 37-03

PATENT

Docket: CU-2649

COMBINED DECLARATION AND POWER OF ATTORNEY

(ORIGINAL, DESIGN, NATIONAL STAGE OF PCT, SUPPLEMENTAL, DIVISIONAL, CONTINUATION OR CIP)

As a below named inventor, I hereby declare that:

TYPE OF DECLARATION

This declaration is of the following type: *(check one applicable item below)*

- ☐ original
- ☐ design
- ☐ supplemental

Note: If the Declaration is for an International Application being filed as a divisional, continuation or continuation-in-part application, do not check next item; check appropriate one of last three items.

- ☒ national stage of PCT

Note: If one of the following 3 items apply, then complete and also attach ADDED PAGES FOR DIVISIONAL, CONTINUATION OR CIP.

- ☐ divisional
- ☐ continuation
- ☐ continuation-in-part (CIP)

INVENTORSHIP IDENTIFICATION

WARNING: If the inventors are each not the inventors of all the claims, an explanation of the facts, including the ownership of all the claims at the time the last claimed invention was made, should be submitted.

My residence, post office address and citizenship are as stated below, next to my name. I believe that I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter that is claimed, and for which a patent is sought on the invention entitled:

TITLE OF INVENTION

WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

SPECIFICATION IDENTIFICATION

the specification of which: *(complete (a), (b) or (c))*

☐ (a) is attached hereto.

☐ (b) was filed on ______________ as ☐ Serial No. ______________ or
☐ Express Mail No. *(as Serial No. not yet known)* ______________
and was amended on ______________ *(if applicable)*.

Note: Amendments filed after the original papers are deposited with the PTO that contain new matter are not accorded a filing date by being referred to in the Declaration. Accordingly, the amendments involved are those filed with the application papers or, in the case of a supplemental Declaration, are those amendments claiming matter not encompassed in the original statement of invention or claims. See 37 CFR 1.67.

☒ (c) was described and claimed in PCT International Application No. PCT/AU00/00219 filed on 20 March 2000 and as amended under PCT Article 34 on 04 July 2001.

ACKNOWLEDGEMENT OF REVIEW OF PAPERS AND DUTY OF CANDOR

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information, which is material to patentability as defined in 37, Code of Federal Regulations, § 1.56,

(also check the following items, if desired)

☐ and which is material to the examination of this application, namely, information where there is a substantial likelihood that a reasonable Examiner would consider it important in deciding whether to allow the application to issue as a patent, and

☐ in compliance with this duty, there is attached an information disclosure statement, in accordance with 37 CFR 1.98.

PRIORITY CLAIM (35 U.S.C. § 119(a)-(d))

I hereby claim foreign priority benefits under Title 35, United States Code, § 119(a)-(d) of any foreign application(s) for patent or inventor's certificate or of any PCT international application(s) designating at least one country other than the United States of America listed below and have also identified below any foreign application(s) for patent or inventor's certificate or any PCT international application(s) designating at least one country other than the United States of America filed by me on the same subject matter having a filing date before that of the application(s) of which priority is claimed.

(complete (d) or (e))

☐ (d) no such applications have been filed.

☒ (e) such applications have been filed as follows.

Note: Where item (c) is entered above and the international application which designated the U.S. itself claimed priority check item (e), enter the details below and make the priority claim.

PRIOR FOREIGN/PCT APPLICATION(S) FILED WITHIN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO THIS APPLICATION AND ANY PRIORITY CLAIMS UNDER 35 U.S.C. § 119(a)-(d)

COUNTRY (OR INDICATE IF PCT	APPLICATION NUMBER	DATE OF FILING (day/month/year)	PRIORITY CLAIMED UNDER 35 USC 119
Australia	PP 9307	18 March 1999	☒ YES NO ☐
			☐ YES NO ☐

CLAIM FOR BENEFIT OF PRIOR U.S. PROVISIONAL APPLICATION(S) (35 U.S.C. § 119(e))

I hereby claim the benefit under Title 35, United States Code, § 119(e) of any United States provisional application(s) listed below:

PROVISIONAL APPLICATION NUMBER	FILING DATE

ALL FOREIGN APPLICATION(S), IF ANY, FILED MORE THAN 12 MONTHS (6 MONTHS FOR DESIGN) PRIOR TO THIS U.S. APPLICATION

Note: If the application filed more than 12 months from the filing date of this application is a PCT filing forming the basis for this application entering the United States as (1) the national stage or (2) a continuation, divisional, or continuation-in-part, then also complete ADDED PAGES TO COMBINED DECLARATION AND POWER OF ATTORNEY FOR DIVISIONAL, CONTINUATION OR CIP APPLICATION for benefit of the prior U.S. or PCT application(s) under 35 U.S.C. § 120.

POWER OF ATTORNEY

I hereby appoint the following practitioner(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith *(list name and registration number).*

(13)

Thomas F. Peterson, 24790; Richard J. Streit, 25765; Donald P. Reynolds, 26220; W. Dennis Drehkoff, 27193; Vangelis Economou, 32341; Brian W. Hameder, 45613; Valerie Neymeyer-Tynkov, Reg. 46956; Paul B. West, 18947; Joseph H. Handelman, 26179; Peter D. Galloway 27885; John Richards, 31503; ~~Iain C. Baillie, 24090;~~ Richard P. Berg, 28145

☐ Attached, as part of this declaration and power of attorney, is the authorization of the above-named practitioner(s) to accept and follow instructions from my representative(s).

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DIRECT TELEPHONE CALLS TO:
(Name and telephone number)

(312) 427-1300

DECLARATION

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

SIGNATURE(S)

Note: Carefully indicate the family (or last) name, as it should appear on the filing receipt and all other documents.

Full name of first joint inventor

Michael		BAZYLENKO
(Given Name)	(Middle Initial or Name)	(Family (or Last) Name)

Inventor's signature [signature] × M B.

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2-ꝏ

Full name of second joint inventor

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Inventor's signature ___ × M.S

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